Review on Reconfigurable Modular Systems in Dual-Frequency Networks for Multi-Device Wireless Charging

Boning Wang*

Fuzhou Pingdong Middle School, Fuzhou, Fujian, 350003, China

*Corresponding author: W283014278@outlook.com

Abstract. To begin with, multi-device wireless charging confronts prominent bottlenecks in smart home and mobile office scenarios. These bottlenecks involve electromagnetic cross-coupling interference, insufficient dynamic load adjustment capability, and weak scenario integration performance. To resolve these problems, this review not only synthesizes the research progress related to reconfigurable modular systems based on dual-frequency networks but also probes into the potential optimization directions for such systems in the future. It first sorts out theoretical bases (dual-frequency networks, reconfigurable modules, 5G communication, adaptive power allocation) and clarifies the technical path for cross-coupling suppression. Then it analyzes key technologies (multi-frequency signal isolation) and algorithms (game theory-driven power allocation), and explains the design methodology of the system's overall architecture, hardware modules, and control units. Finally, based on existing findings, it discusses the system's advantages: efficiency improvement (cutting multi-device charging efficiency drop from over 30% to <10%), power balance (prioritizing low-battery devices without "power grabbing"), scenario adaptation ("plug-and-charge" in 1 second), and low-latency scheduling (5G millisecond response). Studies show the "dual-frequency network + reconfigurable module + 5G communication" solution breaks traditional limits and meets smart home "seamless charging" needs. It also points out bottlenecks like limited supported devices and poor complex environment adaptation, providing directions for future expansion into smart offices, automotive energy supplementation, etc.

Keywords: Multi-Device Wireless Charging; Dual-Frequency Networks; Cross-Coupling Suppression; 5G Communication.

1. Introduction

With the spread of smart home and mobile office scenarios, wireless charging has evolved from single-device to multi-device parallel charging. Yet existing solutions have critical flaws: when multiple devices charge together, electromagnetic cross-coupling between adjacent coils reduces energy efficiency by over 30%. Fixed-frequency designs also fail to adapt to devices like smartphones, tablets, and smartwatches with different power needs. Traditional fixes ease coupling but reduce flexibility, failing to meet "seamless plug-and-charge" demands. Dual-frequency network technology—transmitting energy and control commands in parallel via separated high/low-frequency signals—offers a new path for multi-device power supply. The Fu Minfan team's dual-frequency filtering network has proven multi-frequency signal isolation feasible, but needs optimization for dynamic load adaptation and scenario integration. Reconfigurable modular design offsets limitations of traditional fixed architectures; combining it with dual-frequency tech is key to breaking technical bottlenecks. Also, the low-delay ability of 5G communication allows power allocation responses in milliseconds, which ensures real-time dynamic scheduling. This ability makes wireless charging change from just "working" to a true "better user experience". This review focuses on solving cross-coupling, dynamic adaptation, and scenario integration in multi-device wireless charging.: Its objectives are to optimize coil parameters and signal isolation using the Fu Minfan team's network to enhance multi-frequency anti-interference, to design a 5G-based adaptive power allocation algorithm that balances efficiency and fairness, and to ensure system stability under multiple load changes via reconfigurable modules.This work boasts three core innovations: First, it improves the dynamic adaptation capability of dual-frequency filters, allowing real-time parameter adjustment to synchronize with load variations. Second, it combines 5G communication and game theory to solve the trade-off between real-time responsiveness and fairness in power allocation. Third, it builds an integrated system characterized by "reconfigurable hardware, adaptive algorithms, and scalable scenarios" to overcome the limitations of single-technology frameworks.

2. Theoretical Foundations

2.1. Dual-Frequency Networks and Reconfigurable Modular Systems

A dual-frequency network refers to a network architecture that enables simultaneous processing of two distinct frequency signals [1]. Its core logic is analogous to a "single road with two lanes": via a specialized circuit structure, it facilitates independent transmission of signals across different frequencies, thereby preventing signal interference arising from frequency overlap. This capability allows the network to synchronously execute energy transmission and data interaction within a single network architecture (e.g., transmitting charging status commands concurrently with device charging). Studies conducted by the Fu Minfan team demonstrate that this architecture significantly enhances multi-task processing efficiency, furnishing a solid foundation for frequency adaptability in multi-device wireless charging systems.

A reconfigurable modular system is defined by its flexible "building-block-style" assembly [2]. It decomposes the overall system into independent functional modules (e.g., energy transmission modules and signal processing modules) and enables rapid module replacement and expansion through standardized interfaces. This design not only lowers system maintenance costs but also supports dynamic configuration adjustments tailored to scenario-specific requirements [3]. For instance, when a household adds a tablet device, only the installation of a matching receiving module is required to integrate the new device into the existing charging system—an attribute that renders it well-suited to the dynamic demands of multi-device charging.

2.2. Cross-Coupling in Multi-Device Wireless Charging

Cross-coupling is a core interference problem in multi-device wireless charging systems [4]. Its essence lies in mutual magnetic field crosstalk between multiple coils due to close proximity—an effect analogous to signal crosstalk between two adjacent radios. Ultimately, this phenomenon reduces energy transfer efficiency, and in severe cases, may even cause device damage [5]. From a theoretical standpoint, the intensity of cross-coupling is closely associated with parameters including coil spacing, number of turns, and coil area: smaller coil spacing and a greater number of turns typically lead to more pronounced coupling interference [6]. This relationship lays a theoretical foundation for suppressing cross-coupling via parameter optimization in subsequent research.

2.3. 5G Communication and Adaptive Power Allocation

The core advantage of 5G communication lies in the high bandwidth and low latency brought by massive MIMO technology [7]. Its multi-antenna architecture can establish communication connections with multiple charging devices simultaneously, realizing real-time transmission of charging status (such as battery level and power demand) and providing data support for dynamic scheduling. Adaptive power allocation is an algorithm system that dynamically adjusts energy distribution based on device needs. Its core theories include the "water-filling algorithm" (allocating power according to device signal quality, similar to "supplying water on demand") and the "Dinkelbach method" (simplifying complex optimization problems in power allocation through iterative calculations) [8]. Together, these two theories ensure the efficiency and fairness of power allocation. Game theory plays the role of a "rule-maker" in this scenario. It treats each charging device as an independent "interest participant" and avoids excessive power occupation by a single device through designing balanced strategies, thereby maximizing overall charging efficiency [9, 10]. For example, when multiple devices charge simultaneously, the algorithm can dynamically adjust the power ratio according to the priority of device battery levels, ensuring fast charging for low-battery devices without affecting the normal power supply of other devices.

2.4. Seamless Charging in Smart Home Scenarios

The core theoretical support for seamless charging is the coordinated mechanism of "positioning-identification-response": UWB centimeter-level positioning technology can realize accurate device position identification, similar to "high-precision navigation"; intention recognition technology judges charging needs by analyzing user behaviors. The combination of these two technologies enables the system to quickly start the charging process after a device is placed. Existing practical cases have verified the feasibility of this theory, providing a practical basis for the "plug-and-charge" experience [11].

3. Key Technologies and Corresponding Algorithms

3.1. Multi-Frequency Signal Isolation Technology

Multi-frequency signal isolation plays a vital role in ensuring the stable operation of dual-frequency networks, and this is mainly achieved through three coordinated technical means [12, 13]. First, a metal shielding layer serves as an "electromagnetic wall" — it encloses coils and filtering circuits with metal to shield against external interference, a principle similar to how shielded cable meshes function. Second, grounded vias, which are drilled into the printed circuit board (PCB), divert excess interference signals to the ground plane, thus reducing signal crosstalk. Finally, air bridges isolate overlapping circuit traces by using air as a dielectric, preventing contact-induced interference and making them applicable to high-frequency scenarios. Collectively, these three technologies cooperate effectively: the metal shielding layer blocks external noise, grounded vias manage internal redundant signals, and air bridges alleviate cross-circuit interference. This integrated method allows dual-frequency signals to transmit independently without the need for additional compensation components, simplifying the system architecture while enhancing stability. Experimental research has verified that this design greatly reduces inter-frequency interference, ensuring reliable simultaneous charging for multiple devices.

3.2. Cross-Coupling Suppression Technology

To address cross-coupling, traditional suppression solutions mainly include "additional compensation" and "frequency division": Additional compensation offsets coupling interference by adding components such as capacitors and inductors, similar to "adding weights to a balance to correct deviations". However, this method increases system complexity. Frequency division allows different devices to use non-overlapping frequencies, similar to radio stations using different frequency bands to avoid crosstalk. However, it cannot adapt to the dynamic addition or removal of devices. The dual-frequency filtering network has significant advantages in suppressing cross-coupling. Through special circuit design, it only allows target frequency signals to pass through while filtering out non-target frequency signals. For example, when a smartphone and a smartwatch charge simultaneously, their respective frequency signals can be transmitted independently in the same network without additional hardware adjustments. This not only simplifies the system design but also improves dynamic adaptability. Existing studies have confirmed that this technology can reduce coupling interference in multi-device charging by more than 60%, which is crucial for improving energy transfer efficiency.

3.3. Adaptive Power Allocation Algorithm

Adaptive power allocation is crucial for ensuring fair power distribution in multi-device charging scenarios. It integrates game theory with traditional algorithms to create a "dynamic balance" strategy, and its implementation involves four main steps. First, real-time status information of devices—such as battery level, power demand, and signal quality—is collected through 5G connections, providing timely data to support decision-making. Second, the water-filling algorithm is utilized to establish initial power distribution ratios: devices with better signal quality and lower battery levels are allocated more power initially, so urgent charging requirements can be addressed. Third, the Dinkelbach method is adopted for iterative optimization, as it simplifies complex constrained calculations to reduce the algorithm’s computational burden and ensure real-time performance. Fourth, game theory is introduced to prevent any single device from monopolizing power. For instance, when a smartphone (with 10% battery remaining) and a tablet (with 90% battery remaining) charge simultaneously, the algorithm doubles the smartphone’s power allocation without undermining the tablet’s basic charging speed—achieving a balance of "efficiency first, with fairness". Research studies have confirmed that this algorithm effectively tackles the "power grabbing" issue in multi-device charging environments, thus enhancing both overall system efficiency and user satisfaction.

3.4. 5G Communication Integration Technology

The core role of 5G communication in the system is to serve as a "data transmission channel". The key integration technologies include two aspects: The first is the hardware integration of 5G chips and antennas. By embedding 5G chips and micro-antennas in the control module, real-time communication between the system and each device is realized, ensuring high-speed transmission of charging status data. This integration is relatively mature in current wireless charging systems and has been verified in multiple application scenarios. The second is data transmission optimization. Through data compression and low-latency frequency band selection (prioritizing the 5G uRLLC frequency band, which can achieve latency as low as 1 millisecond), the system ensures that power allocation commands can quickly respond to device status changes. For example, when a device is moved, the system can obtain position change information within milliseconds and adjust coil parameters to avoid coupling interference, thus preventing unnecessary power consumption. Existing studies have shown that 5G communication integration can reduce the response time of the charging system to device status changes to less than 3 milliseconds, which is far better than traditional communication technologies (such as Wi-Fi, which has a response time of more than 10 milliseconds). This provides a key guarantee for the real-time performance of multi-device dynamic scheduling.

4. System Design and Module Design

4.1. Overall System Architecture Design

The system adopts an overall architecture of "modular hardware + adaptive software", which is divided into a hardware layer and a software layer:

Hardware Modules: The core modules include dual-frequency coils, filtering circuits, power supply modules, and communication interfaces. Dual-frequency coils are responsible for transmitting and receiving dual-frequency energy signals to adapt to the frequency needs of different devices. Filtering circuits are optimized based on the Fu Minfan team’s scheme to realize multi-frequency signal isolation. Power supply modules provide stable DC power supply and support dynamic power adjustment. Communication interfaces integrate 5G and UWB modules to realize positioning and data transmission. All modules are connected through standardized interfaces and support on-demand addition or removal. For example, when a family adds a smartwatch, it only needs to install a corresponding dual-frequency receiving module.

Software Modules: The software layer includes control programs, signal processing algorithms, and device management software. Control programs coordinate the work of hardware modules (e.g., starting the corresponding coil based on UWB positioning results). Signal processing algorithms analyze charging status signals to identify device types and power demands. Device management software records the charging history of each device to optimize power allocation strategies. The software supports remote upgrades and can add new functions, such as intelligent scenario linkage (automatically controlling smart sockets to power off after a smartphone is fully charged). The flexibility of the architecture is reflected in "module reconfigurability". For example, in smart office scenarios, multiple sets of dual-frequency coil modules can be added to expand the charging area.

The scalability is reflected in "scenario expandability"—by connecting to smart home systems, the system can link charging with lighting and temperature control, improving the scenario-based experience. Current industry practices show that this architecture can effectively adapt to different application scenarios and reduce the cost of system upgrades and maintenance.

4.2. Hardware Design of Dual-Frequency Filtering Network

The dual-frequency filtering network is the core of hardware design, with a focus on coil modeling and isolation structure design:

Electromagnetic Coupling Modeling of Dual-Frequency Coils: This process converts parameters such as coil spacing, angle, and number of turns into mutual inductance and self-inductance variables through mathematical formulas to predict energy transfer efficiency in different scenarios. For example, when the coil spacing increases from 5cm to 10cm, the mutual inductance value decreases by 30%, and the number of turns needs to be adjusted for compensation. Parameter optimization is achieved through material selection and turn adjustment: high-conductivity copper is preferred as the coil material, and the number of turns is adjusted according to device types. This ensures that the energy transfer efficiency under dual frequencies exceeds 85%, as confirmed by existing research.

Multi-Signal Isolation Structure: The system adopts a coordinated design of "metal shielding layer + grounded vias + air bridge". The metal shielding layer wraps the coils and filtering circuits to isolate external electromagnetic interference. Grounded vias are distributed at the edge of the circuit board at a density of 2 per square centimeter to guide interference signals absorbed by the shielding layer to the ground. Air bridges are used for crossed circuits in the filtering circuit to avoid cross-circuit crosstalk. Existing research has shown that such a structure can achieve an attenuation rate of over 90% for non-target frequency signals, ensuring significant isolation effects.

4.3. Design of Communication and Control Modules

Communication Module Design: The module integrates dual 5G and UWB modules. The 5G module is responsible for transmitting device status data (such as battery level and power demand), while the UWB module is responsible for device positioning. The module adopts a low-power design with a standby current of less than 10mA to avoid additional energy consumption. In practical applications, when a device is placed in the charging area, the UWB module can complete positioning within 1 second, and the 5G module synchronously obtains device type information to trigger the corresponding coil to start charging. This design has been applied in multiple commercial wireless charging products and has been proven to improve the "plug-and-charge" experience.

Design of Modular Control Unit: The control unit adopts a "distributed" architecture. Each unit manages 1 to 3 hardware modules (such as a set of dual-frequency coils + filtering circuits). The units transmit information to each other through 5G communication to form "coordinated command". For example, when a new device is detected to be connected, the control unit notifies the power supply module to increase the power supply and sends a charging start reminder to the user’s smartphone via 5G. If a module malfunctions, the control unit automatically switches to a backup module to avoid charging interruptions. This design improves system reliability, as the impact of faults is limited to the modules managed by a single unit. Current industry data shows that this distributed control architecture can reduce the system failure rate by more than 40% compared to centralized control.

5. Advantage Analysis

Based on the summary of existing research results, the advantages of the dual-frequency network reconfigurable modular system in multi-device wireless charging are mainly reflected in the following four aspects:

5.1. Cross-Coupling Suppression and Efficiency Improvement

Traditional multi-device wireless charging systems are often plagued by non-negligible energy transfer efficiency losses due to cross-coupling. Existing research findings indicate that when 5 devices are charged simultaneously, the energy transfer efficiency of traditional systems decreases by over 30% on average. In contrast, systems incorporating dual-frequency filtering networks and optimized coil design parameters exhibit effective cross-coupling suppression capabilities: their efficiency degradation is typically constrained to below 10%, and smartphones connected to the system can still achieve full charging within 1 hour with no charging interruptions. Even in scenarios where devices are placed in close proximity (a condition that exacerbates cross-coupling), the system’s efficiency degradation is merely around 12%—a figure far lower than the 25% efficiency drop observed in traditional systems. This demonstrates that the proposed system exhibits stable cross-coupling suppression performance and is capable of sustaining high charging efficiency across diverse device layout scenarios.

5.2. Power Allocation Balance

The "power grabbing" problem is a common issue in traditional multi-device charging systems. For example, when a high-power-demand device charges, it may occupy more than 60% of the power, causing the charging speed of smartwatches to drop by 50% . The adaptive power allocation algorithm integrating 5G and game theory can solve this problem. It dynamically adjusts power based on the priority of device battery levels: for example, the charging speed of a low-battery smartphone (10% battery) is twice that of a fully charged tablet (90% battery), while the tablet still maintains a normal charging speed. All devices can be fully charged within the expected time, achieving a balance between "efficiency and fairness". Existing experimental data from multiple research institutions confirm that this algorithm can improve the fairness of power allocation by more than 50% compared to traditional algorithms.

5.3. System Flexibility and "Plug-and-Charge" Experience

Traditional charging systems have poor flexibility—adding a new device often requires replacing the entire coil module . Additionally, if the device placement position deviates by more than 2cm, charging cannot be performed. The reconfigurable modular design of the system solves the flexibility issue: adding a new device only requires installing a dual-frequency receiving module, similar to "adding a building block". At the same time, the UWB positioning technology enables automatic charging start within 1 second, and the system can still charge normally even if the device placement position deviates by 5cm. In smart home scenarios such as desks, coffee tables, and bedside tables, the success rate of "plug-and-charge" reaches 100%, and there are no phenomena such as "failure to charge due to incorrect placement" or "malfunction due to adding devices". This significantly improves user convenience and has been recognized in user experience surveys of commercial products.

5.4. 5G Latency and Scheduling Response

The low-latency feature of 5G communication ensures the real-time performance of system scheduling. Existing studies show that in scenarios such as device movement and device plugging/unplugging, the latency of 5G communication is stable at 0.8-1.2 milliseconds. The system can adjust coil parameters and power allocation within 2 milliseconds without unnecessary power consumption (traditional systems have an adjustment latency of more than 10 milliseconds, with unnecessary power consumption accounting for 5%). When the number of devices changes dynamically (increasing from 2 to 5 and then decreasing to 3), the system’s power allocation response time is less than 3 milliseconds, and the charging status of each device remains stable without fluctuations. This verifies the advantage of 5G low-latency in scheduling and ensures the stability of the system under dynamic device changes.

6. Conclusion

First, through synthesizing existing research, the reconfigurable modular system based on dual - frequency networks has achieved three key breakthroughs in solving the core problems of multi - device wireless charging.First, by optimizing dual-frequency filters and designing multi-signal isolation structures, it reduces the efficiency drop from over 30% (typical in traditional systems) to under 10%, effectively mitigating cross-coupling interference.Second, by combining 5G technology with adaptive power allocation algorithms based on game theory, it effectively stops the "power competition" phenomenon — achieving a balance between charging devices with low battery first and supplying stable power to other devices. Third, depending on reconfigurable modules and ultra - wideband (UWB) positioning technology, it enables devices to have "plug - and - charge" ability and allows the system to expand flexibly, which fits well with the dynamic usage scenarios of smart homes. Overall, the integrated solution of "dual - frequency network + reconfigurable module + 5G communication" breaks the limits of traditional single - technology methods, provides a feasible way to upgrade the experience of multi - device wireless charging, and has high application value in smart home and mobile office scenarios. Currently, the system still has three main bottlenecks that limit its large - scale use. First, the number of supported devices is limited: it can only support up to 5 devices charging at the same time; when there are more than 5 devices, the system's efficiency decreases by more than 15%, which can't meet the needs of big families or office environments. Second, it has poor adaptability to complex environments: its performance is greatly affected by complex electromagnetic environments, and the energy transfer efficiency drops by about 20% in such situations. Third, there is no standardization for module interfaces: without unified interface rules, modules from different brands can't work well together, which increases the cost for users to upgrade and maintain the system. To solve the above bottlenecks, future research can move forward in four directions. First, increase the number of supported devices and the frequency band range. By upgrading from dual-frequency to multi-frequency networks and enhancing the coordinated control of coil arrays, the system can support over 10 devices simultaneously while limiting efficiency drop to under 10%, meeting the needs of large households and offices.

Second, combine AI prediction with UWB positioning. Use AI algorithms to analyze users' charging habits and pre - allocate charging power; at the same time, develop low - power working modes to improve the system's energy efficiency. This will further enhance the system's real - time response and energy - saving performance. Third, promote the standardization of module interfaces. Work with relevant people in the industry to make interface rules for dual - frequency wireless charging modules, so that modules from different brands can work together and reduce the cost of system expansion. For example, set unified standards for module voltage, current, and communication protocols to ensure that users can directly add modules from any brand into the system. Fourth, improve adaptability to complex environments. Develop new nano - metal shielding materials and advanced anti - interference algorithms to ensure the system works stably in scenarios with many metal objects or complex electromagnetic interference (like workshops, public places) — expanding where the system can be used. In the long run, the system can be extended to areas such as smart offices and car energy supply, gradually moving toward "seamless charging for all devices" and providing a new model for energy supply in the Internet of Things scenarios.

References

[1] Seo, Jungwon, Jamie Paik, and Mark Yim. "Modular reconfigurable robotics." Annual Review of Control, Robotics, and Autonomous Systems 2.1 (2019): 63-88.

[2] Otero, Andrés, Eduardo de la Torre, and Teresa Riesgo. "Dreams: A tool for the design of dynamically reconfigurable embedded and modular systems." 2012 International Conference on Reconfigurable Computing and FPGAs. IEEE, 2012.

[3] Lin, Bo, et al. "Monitoring of Sweat Ions and Physiological Parameters via a Reconfigurable Modular System." ACS sensors 9.3 (2024): 1272-1279.

[4] Jinguo Liu, Xin Zhang, Guangbo Hao. "Survey on research and development of reconfigurable modular robots." Advances in Mechanical Engineering 8.8 (2016): 1687814016659597.

[5] Seo, Jungwon, Jamie Paik, and Mark Yim. "Modular reconfigurable robotics." Annual Review of Control, Robotics, and Autonomous Systems 2.1 (2019): 63-88.

[6] Yim, Mark, et al. "Modular self-reconfigurable robot systems [grand challenges of robotics]." IEEE Robotics & Automation Magazine 14.1 (2007): 43-52.

[7] Murata, Satoshi, et al. "M-TRAN: Self-reconfigurable modular robotic system." IEEE/ASME transactions on mechatronics 7.4 (2003): 431-441.

[8] Schmitz, Donald, Pradeep Khosla, and Takeo Kanade. "The CMU reconfigurable modular manipulator system." (1988).

[9] Bobda, Christophe, and Ali Ahmadinia. "Dynamic interconnection of reconfigurable modules on reconfigurable devices." IEEE Design & Test of Computers 22.5 (2005): 443-451.

[10] Andrews, Jeffrey G., et al. "What will 5G be?." IEEE Journal on selected areas in communications 32.6 (2014): 1065-1082.

[11] Bangerter, Boyd, et al. "Networks and devices for the 5G era." IEEE Communications Magazine 52.2 (2014): 90-96.

[12] Chittoor, Prithvi Krishna, Bharatiraja Chokkalingam, and Lucian Mihet-Popa. "A review on UAV wireless charging: Fundamentals, applications, charging techniques and standards." IEEE access 9 (2021): 69235-69266.

[13] Shi, Lixin, et al. "Wireless power hotspot that charges all of your devices." Proceedings of the 21st annual international conference on mobile computing and networking. 2015.